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THE HISTORY OF THE QUANTITY DISTANCE TABLES FOR EXPLOSIVE SAFETY

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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The history of the quantity-distance tables for explosive safety is traced from its inception to the present. Comparisons are made to alternative approaches used by NATO and other countries. There exist only minor differences in safety distances at this time. U.S. distances are more conservative for quantities less than 1000 lbs and less conservative for larger quantities. Projections are also made as to the effect of packaging changes, and containerization of ammunition shipments on future explosive safety standards.

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I. INTRODUCTION

The Ballistic Research Laboratory (BRL) is investigating the mechanisms for initiation of detonation of stored munitions. The goal of this effort is to reduce the vulnerability of stored munitions, and prevent or reduce the probability of propagation of explosion between adjacent munitions stores. Application of the techniques developed will range from small quantities, such as might be found in armored vehicles to larger quantities encountered in shipment, or in storage depots. As part of this program an investigation has been made of the source and development of quantity-distance regulations as defined in AMCR-385-100[1] and TM 9-1300-206[2]. It is the results of this investigation which will be reported here.

II. QUANTITY-DISTANCE TABLES

There are a number of different quantity-distance tables, the application of which depend on the nature of the potential threat, and the degree of protection required. Different nations have differing standards to be met, but there is a trend toward agreement on standards. This is exemplified by the recent adoption (1977) of the United Nations classification system by the United States, United Kingdom and many NATO countries. For the US Army, ammunition and explosives are classified on the basis of their reactions to specified initiating influences as described in TB 700-2[3].

The classification system recommended for international use by the United Nations consists of nine classes for dangerous goods with ammunition and explosives included in UN class 1, explosives. Class 1 explosives are subdivided into four parts as follows. Class 1.1 represents explosives and ammunition which when stored or shipped with only small separation distance between items, and may detonate "en masse". Class 1.2 is for fragment producing cased explosives, such as projectiles. This class is further subdivided into four subclasses dependent on the range of the fragment threat in feet, i.e., 400, 800, 1200, or 1800 feet. This is designated as 1.2 (04), 1.2 (08), 1.2 (12) or 1.2 (18). Class 1.3 is for materials which represent a severe fire threat. Class 1.4 is for materials which represent a moderate fire threat. Table I shows the UN hazard classes with the appropriate conversion from the superceded US classification system. This table was extracted from AMCR 385-100[1] Change 3, dtd 4 October 1977, Chapter 19.

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[1] *US Army Material Command Regulation 385-100, with Change 3, dated 4 October 1977.*

[2] *US Army Technical Manual TM 9-1300-206, dated August 1973.*

[3] *TB 700-2, "Explosives Hazard Classification Procedures," with Change 1, dated May 1967.*

Table I. Conversion From Superceded US Hazard Classification System to UNO System

Superceded Class	UNO Class	Hazard
7	1.1	Mass detonation with possible fragment threat
6	1.2 (18)	Non mass detonating
5	1.2 (12)	with most fragments
4	1.2 (08)	falling within the
3	1.2 (04)	distance indicated
2	1.3	Mass fire
1	1.4	Moderate fire

The common quantity-distance tables are listed below with their definitions as they are given in AMCR 385-100[1], Chapter 17.

- Inhabited Building Distance. This distance is the minimum permissible distance allowed between a quantity of explosives and any building inhabited by the public or where people are accustomed to assemble, both within and outside government establishments. Land outside the boundaries of government installations is included as a possible site for inhabited buildings. This minimum distance provides a high degree of protection against structural damage based on blast or shock wave effects to frame or masonry buildings. It does not provide protection against glass breakage. Personnel injury from flying glass fragments is a possibility.

- Public Traffic Route Distance. This distance is the minimum permissible distance between an explosives site and public highways or railroad lines. It is 60% of the inhabited building distance. The lesser distance is based on the greater resistance of rail and road vehicles to blast effects. It is additionally reasoned that safety is not compromised because these items are only exposed for limited periods as they pass by the explosive site.

- Intraline Distance. This is the minimum permissible distance between two buildings within one operating explosive/ammunition production line. The purpose of the intraline distance is to prevent the propagation of explosions by blast effects between buildings. Separation of service magazines is an example. Distances are based on the larger quantity of explosives involved in either building.

- Magazine Distance. This is the minimum permissible distance between storage magazines, and is based on the type of magazine and the quantity of explosive involved. It is designed to prevent propagation of explosives by blast, and provides reasonable protection against propagation by fragment impact. It does not preclude severe structural damage to magazines adjacent to a magazine suffering an accidental explosion.

• Fragment Distance. This distance applies to specific explosive items which generate hazardous fragments, such as fragmenting projectiles and heavily cased explosives. For the specified distance the fragment distribution and energy is, less than one fragment of energy 58 ft-lbs per 600 square feet, (78 Joules per 56 m^2). This distance applies to class 1.2 items with distances as previously described of 400, 800, 1200 and 1800 feet. This distance also is the inhabited building distance for class 1.2 items and is designated to protect individuals in the open from fragment threats.

Excluding the fragment distance, which is specific for each munition, the remaining distances each correspond to a specific scale distance $Z = R/W^{1/3}$, where R is the distance in feet from the explosive and W is the weight of the explosive in pounds. The scale distance can be related to a specific value of overpressure. Table II gives the 1977 scaled distances for each of the above defined quantity distances used by the United States, and the approximate value of the side-on-pressure associated with each scale distance.

Table II. Scale Distance and Side-On-Pressure For Specified Quantity-Distance Categories

Quantity Distance	Scale Distance	Side-On-Pressure p.s.i.
Inhabited Building		
1 to 100,000 lbs	40	~ 1.1
100,000 to 250,000 lbs	40→50	
250,000 to 1,500,000 lbs	50	~ 0.93
Public Traffic Route		
1 to 100,000 lbs	24	~ 1.8
100,000 to 250,000 lbs	24→30	
250,000 to 1,500,000 lbs	30	~ 1.4
Intraline	18	~ 2.5
Magazine Distance (dependent of type of magazine)	1.1→11	~ 700 → 5.3

III. HISTORICAL BACKGROUND[4,5]

The Inhabited Building Distance Tables, or "The American Table of Distances" as it was called earlier, had its genesis in 1909. In that year Col. B. W. Dunn, Chief Inspector of the Bureau of Explosives, representing the American Railroad Association, brought to the attention of the manufacturers of explosives in the United States a potentially hazardous situation. He demonstrated the need for some radical changes in the location of explosive magazines with respect to railway lines. As a result of Col. Dunn's efforts the Association of Manufacturers of Powder and High Explosives appointed a committee to study the problem. Foreign regulations were examined, but were not found to be suitable, and an extensive investigation of explosive accidents world-wide was undertaken. The principle data compiled were the quantity of explosive involved in an accident, and the distance to which damage extended. The committee assembled descriptions of the accidents, and tried to assess the extent of the damage for 122 explosive accidents between the years 1864 and 1914. These descriptions along with eighteen additional explosive accidents are included in Assheton's[4] work.

As a result of this study the American Tables of Distances was published which gave the minimum permissible distance allowed for inhabited buildings for quantities of explosive up to 1,000,000 pounds. Assheton noted that the table could be approximated quite well by a curve which related the distance to a constant times the cube root of the explosive weight, but this was not exploited until much later. In compiling the data on the accidental explosions it was always noted, as to whether or not, the explosive source was barricaded, either naturally or artificially. This led to the interesting assumption, that if the source was barricaded then the safe distance was half that of an unbarricaded source of like weight. There was no explanation or justification given for this assumption, and it later caused much debate within groups charged with explosive safety regulations. Railroad distances were set at 60 percent of the inhabited building distance and public highway distances at half the railroad distance. The highway distance was later changed to the same value as railroad distances. The selection of 60% was rather arbitrary and the reasoning is given in the following quotation from Assheton[4].

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[4] *Assheton, Ralph, History of Explosions on Which the American Table of Distances was Based, Published under the direction of the Institute of Makers of Explosives, Charles Story Press Co., Wilmington, Delaware, 1930.*

[5] *House of Representatives Document No. 199, "Ammunition Storage Conditions," Proceedings of the Joint Army-Navy Board to Survey Ammunition Storage Conditions Pursuant to Public Law, No. 2, 70th Congress, 1928, AD 493 245.*

"... after as careful a consideration as possible, it was concluded that reasonably safe distances from railroads were provided by taking 60% of the inhabited building distances, the reasons for the conclusion being:

The lesser height and small area of railroad cars exposed to resist concussion, as compared with buildings.

The fact that while a building is stationary and subject to any risk constantly, the presence of a train is only temporary."

It is interesting to note that the wording in AMCR 385-100[1], Chapter 17, paragraph 3 is very nearly identical to the above quotation.

The American Table of Distances was established in 1915. The state of New Jersey adopted them as state law in 1925 and the United States Government adopted them in 1928 following the Lake Denmark accident[5], which incidently marked the beginning of what now is the Dept. of Defense Explosive Safety Board. The most remarkable aspect of this table was that in spite of the large scatter in the data (see Figure 1), and the reliance that had to be placed on subjective accounts of the accidents, often several years old; these tables are remarkably close to modern accepted values. The tables remained unchanged for many years. In fact they are given exactly as published in a 1942 US Army Ordnance School Text[6] and in a 1960 explosives handling manual[7].

In 1945 Col. C. S. Robinson who was attached to the Army/Navy Explosive Safety Board published a report[8] in which he questioned the accuracy of the inhabited building distance tables. His primary concern was for large quantities of explosives. He believed the distances specified were inadequate. He was also concerned that modern explosives, being more energetic per unit weight, might also make the distances specified too short for safety. His concern was based primarily on damage resulting from accidents involving large quantities of explosives, and the fact that World War II mobilization resulted in large quantities of munitions being stored in various port areas. Figure 2 shows the American Table of Distances with data points that were the basis of his

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[6]*Ordnance School Text OS 9-18, Vol. 5, Ammunition General, Part IX Storage, November 1942.*

[7]*ARMTC-TR 60-11, Manual for Handling Explosives, Ammunition and Solid Propellants, Section I, pages 1-24. Contractor Report compiled by Pan American World Airways. AD 710 180.*

[8]*Col. Clark S. Robinson, Army-Navy Explosive Safety Board, Technical Paper Number 1, "The Present Status of the American Table of Distance," 1 July 1945.*

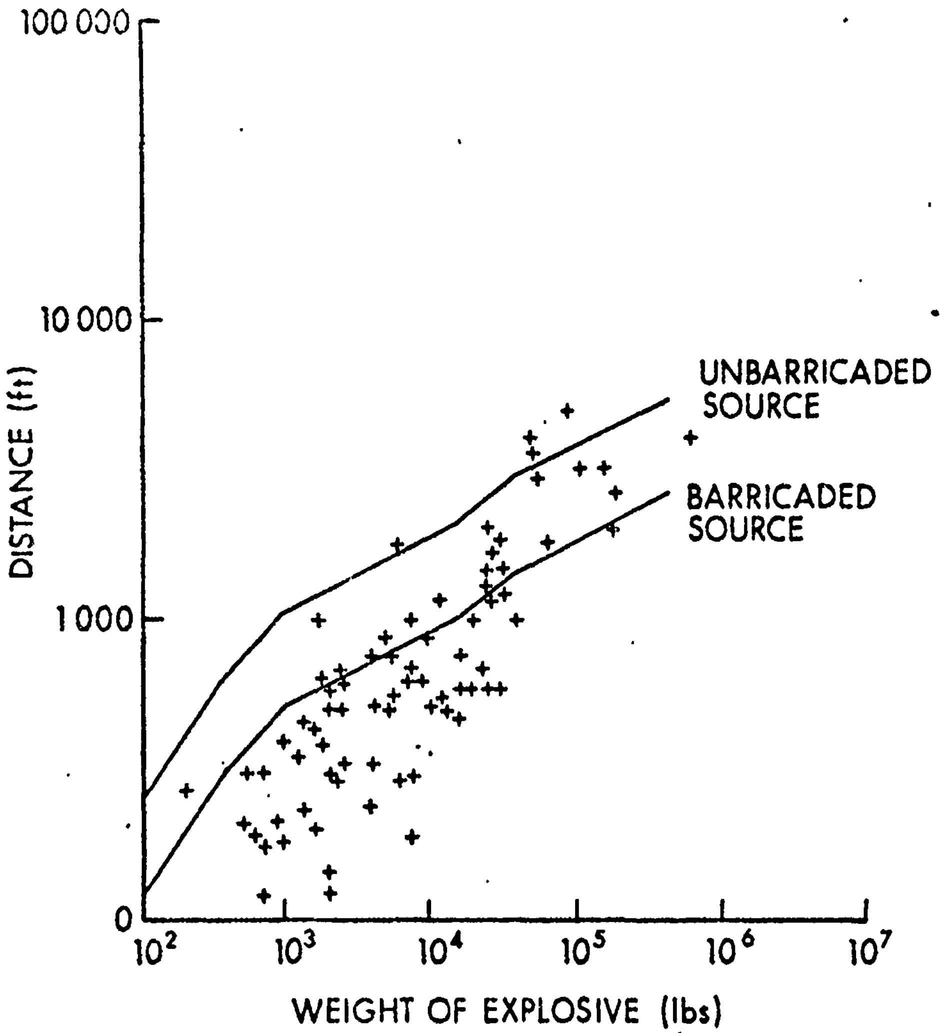

Figure 1. 1915 Inhabited Building Distance Curves with Data Points on Which They Were Based

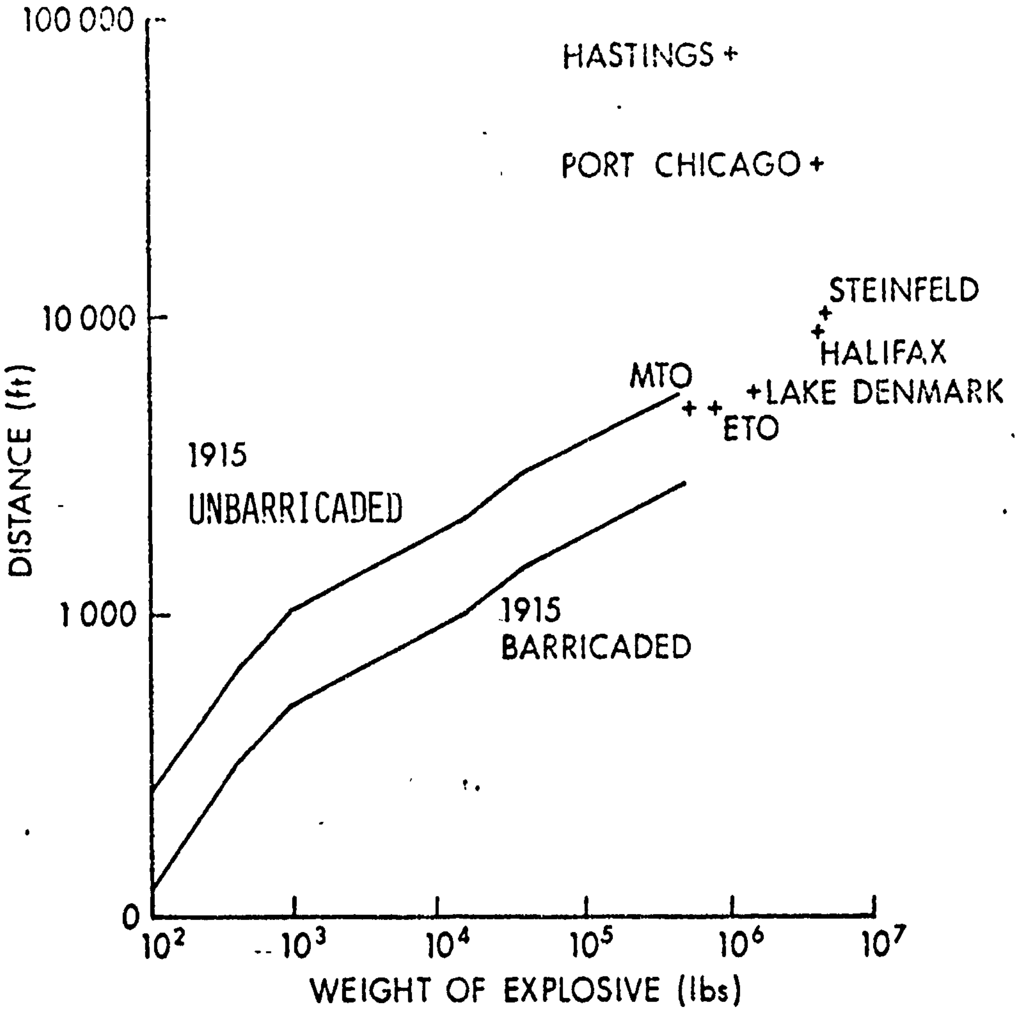

Figure 2. 1915 Inhabited Building Distances with Data Points for Some Large Accidents

concern. Adding to Col. Robinson's concern may have been the accidents at Port Chicago and at Hastings the previous year. Both involved large quantities of Torpex, which was known to be more sensitive than TNT and to have a greater air blast effect. Col. Robinson also questioned the efficacy of barricades at the source in reducing safe distances in this report. He is largely responsible for the work that was initiated following World War II to increase the knowledge and understanding of explosives and their effects.

In the period following the end of World War II extensive explosive blast research was undertaken at many government laboratories. Assheton had noted in 1930 that the American Table of Distances could be approximated by a constant times the cube root of the explosive weight. Extensive testing and measurement of blast pressures under carefully controlled conditions validated this concept. Protection from the effects of blast are now related to a specific scaled distance, as indicated in Table II. Assheton's 1930 value for barricaded explosive sites was 35. The 1977 value for inhabited building distance is 40 for quantities of explosive up to 100,000 lbs and 50 for quantities in excess of 250,000 lbs.

The effectiveness of barricades in reducing blast pressures was a topic that received a great deal of attention in the twenty year period following World War II. Col. Robinson had questioned the efficacy of barricades in his 1945 paper[8] and dealt more extensively with the topic in his book[9]. The Armed Services Explosive Safety Board sponsored a large amount of work to produce data addressing the problem. The difficulty encountered in removing barricaded distances from the inhabited building distance tables is illustrated in a presentation to the Armed Services Explosive Safety Board by the Defense Atomic Support Agency in 1966[10]. In addition to the data and conclusions presented, this report includes a transcript of the discussions following each presentation. The reluctance to abandon the concept that barricades at the source can reduce safe distances for inhabited buildings is clearly evident. A second DASA paper[11] published in 1968 gives a very good summary of the available data and a very complete bibliography of pertinent publications. Barricades were proven to be less effective than previously supposed at distances more than 5 to 8 times the barricade height. As a result the barricaded distance values were eliminated from inhabited

[9] *Col. Clark S. Robinson, Explosions, their Anatomy and Destructiveness, McGraw Hill, New York, 1944.*

[10] *"Barricaded vs Unbarricaded Blast Pressure-Distance Relationships," a Presentation to the Armed Services Explosive Safety Board by the Defense Atomic Support Agency, 12 July 1966, presenters were: Jack R. Kelso, DASA; William S. Filler, Naval Ordnance Laboratory; and Kenneth Kaplan, URS Corp., AD 835 629.*

[11] *URS 677-4R, DASA 2014, "Effectiveness of Barricades: Review of Basic Information," K. Kaplan and V. W. Davis, URS Corp., June 1968, prepared for Defense Atomic Support Agency, AD 837984.*

building distance tables.

In an attempt to better predict and quantify blast damage to specific targets and target elements, generally in a vulnerability analysis context several authors have incorporated impulse loading with pressure loads to predict a specified damage level. In general curves representing a constant level of damage can be obtained in the pressure-impulse plane. Johnson[12] and Baker[13] show several examples, the former for total targets and the latter for structural elements. In every case the response of the target and failure mode must be specified. Sewell[14] reported a similar technique in 1964 and more recently Schumacker and Cummings[15] have presented a pressure-impulse blast damage mode. Falcon Research and Development Co.[16] under contract to the Armed Services Explosive Safety Board developed models of blast response for ten specified targets. The targets were selected as typically those encountered in quantity-distance tables i.e., a house, public buildings, magazines, aircraft, and vehicles. The models were dynamic interaction models and considered both elastic and plastic deformation of the principle structural elements of each target, and specified acceptable damage levels. A computer program was generated to handle the computations. Where possible, comparison is made to actual test data. Calculations were made for five charge weights ranging from 1000 lbs to 9,000,000 lbs. The resulting isodamage curves in the pressure-impulse plane are hyperbolic and similar to those of Johnson[12] and Baker[13].

Figure 3 shows a comparison of the predicted response of a split level ranch style home, and an A frame church structure to current inhabited building distance curves. The specified acceptable damage level for the house is the cracking, but not breaking of the rafters (2" x 8" x 17 feet long, 16 inches on center with 1/2" plywood roof). The specified acceptable damage level for the church was the cracking, but not breaking of laminated roof trusses (7.5" x 16" x 39 feet long, 15 feet on center with a roof of 4" x 8" tongue and groove planks). As can be seen from Figure 3 the house data points fall very nearly on the inhabited building distance curve, but the data points for the church indicate inadequate protection for charge weights in excess of 5000 lbs.

[12] *Johnson, O. T., "A Blast-Damage Relationship," BRL R 1389, Ballistic Research Laboratory, September 1967, AD 389 909.*

[13] *Baker, W. E., et al, "Workbook for Predicting Pressure Wave and Fragment Effects of Exploding Propellant Tanks and Gas Storage Vessels," NASA CR-134906, November 1975.*

[14] *Sewell, R.G.S., "A Blast Damage Criterion," US Naval Ordnance Test Station, China Lake, CA, NOTS TP 3426, March 1964, AD 349335.*

[15] *Schumaker, R. N. and Cummings, B. E., "A Modified Pressure-Impulse Blast Damage Model," Ballistic Research Laboratory BRL MR 2724, January 1977.* (AD #A036196)

[16] *Custard, G. M., Donahue, J. D., and Thayer, J. R., "Evaluation of Explosive Storage Safety Criteria," May 1970, prepared for Armed Services Explosive Safety Board, AD 871 194.*

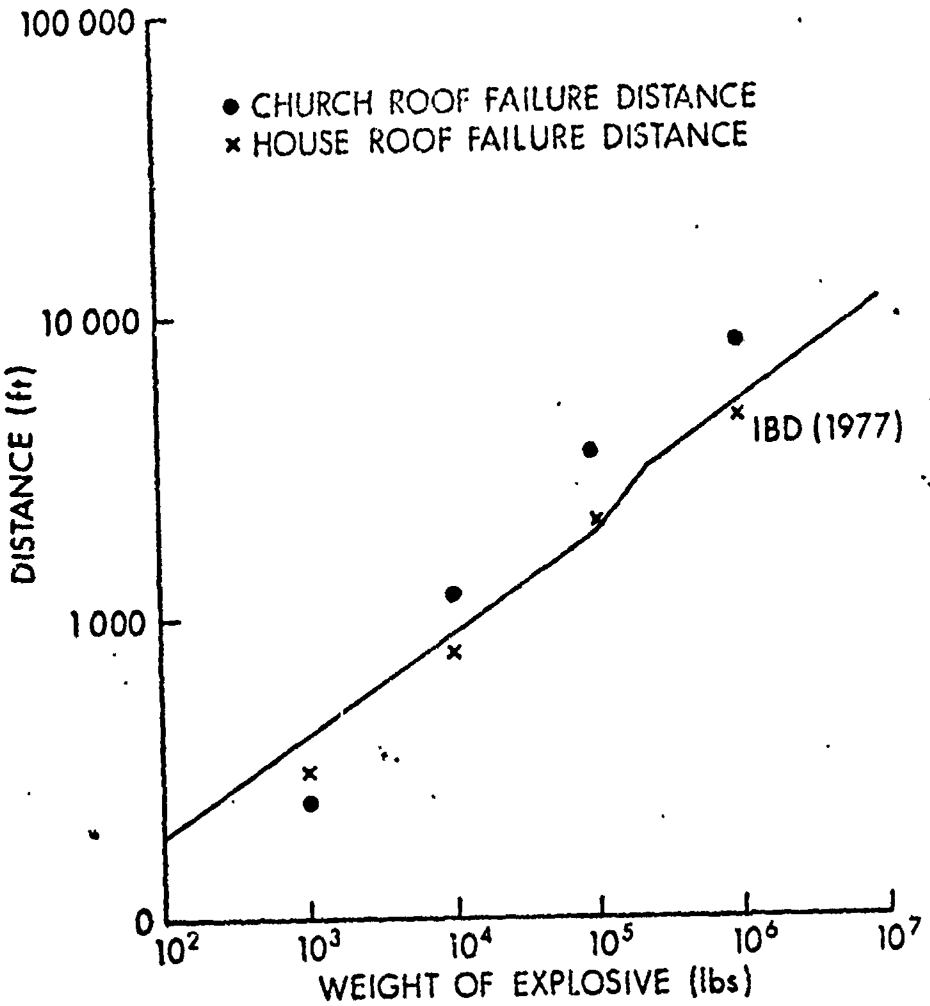

Figure 3. Comparison of 1977 Inhabited Building Distance to Structural Failure Distances Calculated by Falcon Pressure-Impulse Loading Technique

Figure 4 is a similar comparison between calculated safe distances (targets are not overturned) for a bus, a pickup truck with camper, and a house trailer all on a highway, and public traffic route distances currently in effect. In this case the bus, which is the more resistant to overturning of these targets, has a safe distance nearly coincident with public traffic route distances, except for very large charge weights. The other two targets are likely to be overturned at the public traffic route distances. This demonstrates how important the target response and failure mode are to calculating safe distances by this technique. Because the target response is so important to the calculation of safe distances, and because of the diversity of targets that must be protected at inhabited building distances and at public traffic route distances it is unlikely that this technique, which requires computer calculations will have any marked effect on the quantity distance tables. Exceptions might well be made however for those situations where large quantities of explosive are stored or where the public is encroaching on territory adjacent to large storage sites. Other possible exceptions might be special construction at inhabited building distances which by its nature may be more vulnerable to blast damage, for example a curtain wall building with large expanses of glass windows.

IV. CURRENT STATUS OF QUANTITY DISTANCE TABLES

The current US Inhabited Building Distances are compared to the 1977 NATO standards[17] in Figure 5. As can be seen the US values are more conservative for quantities less than 1000 lbs, and less conservative for larger quantities. For example at 10,000 lbs NATO standards require 1206 feet compared to 865 feet to meet US standards and for 100,000 lbs the values are 2600 feet NATO vs 1855 feet US. (NOTE: NATO standards are in metric units.

$$D = 22.2\ Q^{1/3} \text{ for } > 4500 \text{ kg}$$

$$D = 5.5\ Q^{1/2} \text{ for } < 4500 \text{ kg}$$

where D is in meters and Q is the weight of the explosive in kg).

The NATO standards[17] for inhabited buildings are based on work reported by the United Kingdom[18] in 1959. In this work standards are multiples of a quantity R_b which stands for the radius of B type damage. "B" damage is defined as: Such severe damage as to require demolition. The data were derived from bomb damage by air blast to buildings during World War II. R_b in terms of explosive weight is given by the formula:

[17] *Manual on NATO Safety Principles for the Storage of Ammunition and Explosives, 1977, AC/258-D/258.*

[18] *Notes on the Basis of UK Outside Safety Distances for Explosives Involving the Risk of Mass Explosion," March 1959, AD 221 164.*

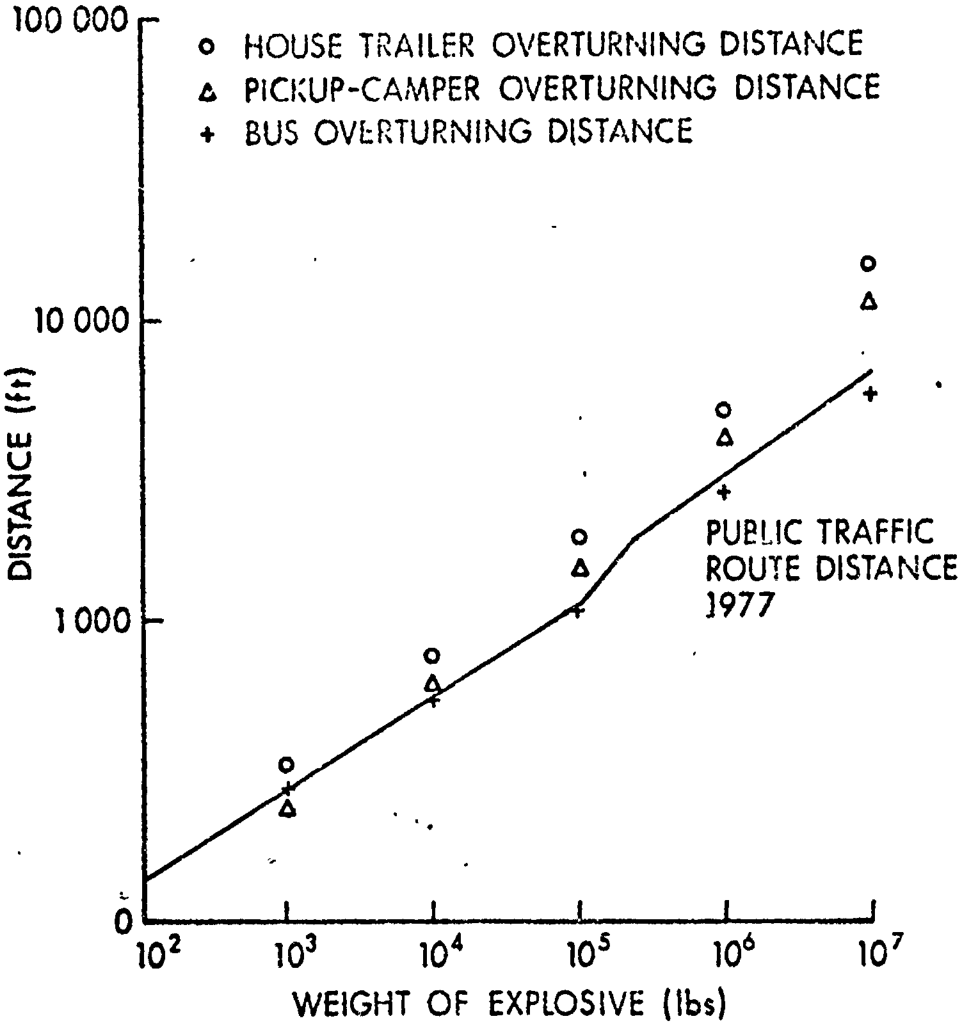

Figure 4. Comparison of 1977 Public Traffic Route Distance to Overturning Distance for Three Vehicles Computed using Falcon Pressure-Impulse Loading

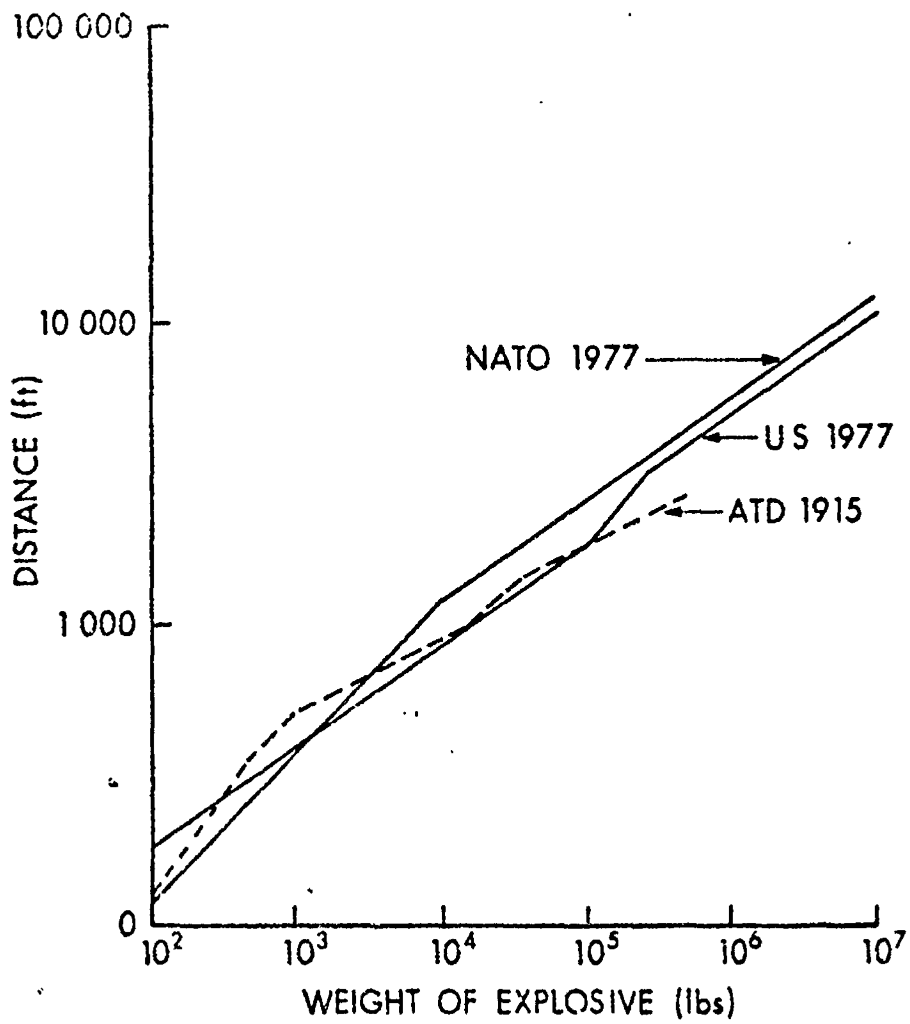

Figure 5. Comparison of the NATO and U.S. 1977 Inhabited Building Distances. Also shown is the 1915 American Table of Distance for a barricaded source.

$$R_b = \frac{14\ W^{1/3}}{\left[1 + \left(\frac{7000}{W}\right)^2\right]^{1/6}}$$

where R_b is in feet and W is the explosive weight in lbs. Inhabited building distances were then set at $4R_b$. For explosive weights in excess of about 10,000 lbs the inhabited building distance is approximated by $4\ R_b = 56\ W^{1/3}$. The above formula was the NATO standard in 1970[19]. Except for the change in units the 1977 NATO standard is the same above 10,000 lbs of explosive. For lesser quantities the expression now used is shown below in both English and metric units.

$R = 12\ W^{1/2}$ R in feet W in lbs.

$D = 5.5\ Q^{1/2}$ D in meters Q in kilograms.

Intermagazine distances and intraline distances appear to be about comparable between the US and NATO standards, although NATO intraline distances are slightly more conservative. An exact comparison is difficult because of differences in definitions and descriptions of donor and acceptor sites.

V. PROJECTIONS

In the author's opinion, there will be little change in the quantity distance tables. The distances for blast damage to general classes of targets are well established from both theoretical and experimental programs. It appears likely that the U.S. and NATO countries will come to an agreement on a mutually acceptable standard, probably in metric units. Donor and acceptor site definitions and descriptions will also probably be standardized. Somewhat less likely, but still possible, is a world wide standard through the UNO analogous to the recently adopted explosive classification system (see Reference 1, change 3, dated October 77).

There exist current programs, within the military explosive research community, which have the potential to result in a severe impact on ammunition storage criteria. The programs do not negate the established quantity distance tables. What they do hope to accomplish is to provide techniques to limit the amount of explosive allowed to participate in an explosive accident. This work is an extension of a concept contained

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[19] *NATO Safety Principles for the Storage of Ammunition and Explosives, 1970, AD 876 078.*

in Reference 5 - a report by the Joint Army-Navy Board to Congress. They said, "It is not the total amount in the depot that should be the guide, but rather the amount in any one pile or building, the manner in which it is stored, and the kinds of explosive that are stored in the vicinity." Current programs seek to extend this concept so that the quantity of ammunition that is allowed to participate in an accidental explosion is limited to some small portion of the ammunition in the stack or storage facility, and so that the reaction violence of the munitions that do participate is minimized. Two major programs supporting these research efforts are Containerized Shipment and Storage of Ammunition[20] (COSSA) and Safe Transport of Munitions[21] (STROM).

The COSSA study is a result of the projected shift in sea lift capability from break bulk cargo ships to a containership fleet. Although the COSSA study is primarily a study of logistics problems, there is a significant impact on safe storage of ammunition. The use of containers for ammunition shipment provides the packaging engineer with a fixed volume and maximum weight with which to work. These constraints, along with maintaining realistic logistic efficiency, still provide the opportunity for packaging at least some munitions in a manner which can limit the participation to a portion of the munitions stored in a container and reduce the violence of secondary reactions. This opportunity has not, as yet, been exploited.

The STROM program is a two pronged attack. First the causes of accidental detonation of munitions during transport are being isolated and eliminated to the extent possible, and second packaging and ammunition design are being investigated to reduce round to round and container to container communication, and reduce the violence of non-design initiated reactions.

There are four principal research areas which derive at least partial support from these programs which have the potential to make significant impact on ammunition storage criteria. They are as follows: (1) research on the mechanisms of fragment impact initiation of cased explosives, (2) the use of buffering material to reduce round to round communication of detonation, (3) modification of munitions design to reduce the violence of reaction in nondesign initiation modes, and (4) modification of explosive fills to make ammunition less susceptible

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[20] *"Containerized Shipment and Storage of Ammunition," Final Draft, Sep 76, ACN 22194, DA, HDQ TRADOC, Fort Monroe, VA., USA Logistic Center, Fort Lee, VA.*

[21] *"Safe Transport of Munitions," Study Plan, revised 7 Jan 77, Military Traffic Management Command Transportation Engineering Agency, Newport News, VA 23606.*

to nondesign initiation. The work of Howe[22,23] at the Ballistic Research Laboratory is an example of research in the first two areas. The phenomena of interround communications and initiation mechanisms are discussed and the effectiveness of various buffering techniques are documented in these works. Mr. Pakulak[24] at Naval Weapons Center, China Lake, has demonstrated the effectiveness of various liner materials, for the Mark 80 series of bombs, in reducing the violence of reaction resulting from cook-off of stacked bombs. He has shown that case rupture can be made to occur in cook-off tests with these munitions, resulting in explosive burning rather than violent detonation. Continuing basic research in explosives and explosive effects within the Army and Navy research communities shows promise of providing explosives which are less sensitive to accidental initiation while maintaining their desired weapon design characteristics.

In summary, it appears that the combination of all these efforts will result, at some future time, in a hazard reduction for many classes of ammunition. Although all these techniques are not applicable to all munitions, they will generally be applicable to most of the high use items of ammunition. It seems likely that some munitions currently classified as hazard class 1.1 may be able to be reclassified at 1.2, at least as long as they are transported or stored in a specified manner. The principal constraints for all of the tasks mentioned above are that weapon effectiveness must not be compromised, and reasonable logistics requirements must still be met. These goals seem to be attainable, and while not directly effecting the quantity distance tables, will reduce the number of kinds of munitions currently classed as mass detonable.

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[22] *Howe, Philip M., "The Phenomenology of Interround Communication and Techniques for Prevention," Ballistic Research Laboratory, ARBRL-TR-02048, Mar 78.* (AD #A054373)

[23] *Howe, Philip and Collis, David, "Effectiveness of Plastic Shields in Prevention of Propagation of Reaction Between Compartmentalized Warheads," Ballistic Research Laboratory, ARBRL-MR-02827, Apr 78. (AD #B027466L)*

[24] *Pakulak, Jack M., "Reduction of Cook-off Hazards," Fifteenth Explosive Safety Seminar, Vol. II, Sep 1973, pp 1263-1272.*

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